THE EVOLUTION OF THE EARLY LUNAR CRUST. P. C. Hess, E.M. Parmentier, Department of Geological Scieneces, Brown University, Providence, R.I. 02912 U.S.A.

Current reconstructions of the lunar crustal stratigraphy are guided by models of impact cratering and the distribution of rock and mineral clasts in the ejecta deposits surrounding multi-ring basins (1,2). These models have an upper crust formed largely of ferroan anorthosite underlain by rocks of aluminous basalt composition. This lower crust is the source of the pervasive and enigmatic low-k Fra Mauro basalts which in some models, are overlain by Mg-Suite rocks of varied types, but dominated by norites and troctolites. This proposed crustal stratigraphy is consistent with magma ocean models which have an ancient anorthosite crust form by plagioclase flotation which is subsequently modified by both impact processes and intrusion by younger mafic magmas. The question that we address, here, are the plutonic and tectonic processes that acted to create the crust in its present configuration. We ask, specifically, why the crust is vertically zoned, why there are no plutonic equivalents to mare basalt, and how the evolution of lunar crust would shape subsequent and younger volcanic events?

We first examine the rheological properties of the ancient anorthosite crust soon after the crystallization of the magma ocean. Specifically, we ask if the crust is strong enough to support the existence of high level plutons of mafic composition. Rheologic studies demonstrate that the crust of terrestrial planets, including the Moon, should be comprised, at low strain rates, of a relatively strong brittle upper layer (typically 10-20km) and for relatively thick crusts, a weaker ductile lower layer (3). The strength of the upper crust is limited by the frictional resistance along faults which to the first order is sensitive only to the normal load and not to temperature or lithology. The lower, weaker crust, if it exists, undergoes steady state plastic flow dominated by dislocation motion, solid state diffusion or solution-deposition processes (not applicable to the dry environment on the Moon). The brittle-ductile transition marks the boundary between these zones.

The strength of the anorthositic crust in the plastic regime which dominates the lower weaker crust can be approximated by the flow laws of ultra-dry Columbia diabase (4). The Columbia diabase is plagioclase rich, roughly 70 vol% of the diabase is composed of anorthite-rich plagioclase, and deformation appears to be localized within the plagioclase grains. Nevertheless, the presence of about 30% pyroxene may make the Columbia diabase slightly stronger then anorthosite under the same conditions of deformation.

The flow law appropriate to "anorthosite" under reducing conditions is highly non-linear (4):

$$\dot{\varepsilon} = 4000\alpha^{4.7}\ e^{-510/RT}$$

where $\dot{\varepsilon}$ is the strain rate, α the stress in MPa and the activation energy is -510 Kj/mol. Note that the strain rate, hence the strength of the rock, is strongly dependent on temperature (°K) (because of the high activation energy) and stress (because of the large stress exponent).

Consider the following scenario. The lunar crust at about 4.4By is composed of largely anorthosite 40km or so in thickness. The temperature at the base of the crust is about 1000-1050°C, the estimated solidus of the magma ocean (5). Consider the intrusion of gabbro or norite magma into the crust. The density of the crust is roughly 2700 kg/m^3 and is similar to the magma at the same temperature and pressure. The liquid pluton is then roughly neutrally bouyant. On crystallization, however, the density of the pluton will increase by about 300 kg/m^3, leading to a density difference of 300 kg/m^3 between the pluton and the surrounding anorthosite. The stress (deviatoric) is calculate from

$$\alpha = gh\Delta\rho$$

where g=1.6m/sec2 is the acceration of gravity, h is the thickness of the pluton in meters and $\Delta\rho$ = 3000 kg/m^3. For plutons 1 to 10 km in thickness, the stress is from 0.5 to 5.0 MPa. Let's assume that the crust is at 1100°K and substituting α = 1 into equation (1); the strain rate is $\dot{\varepsilon} = 8.4 \times 10^{-21}$ and the effective viscosity is

$$\eta = \frac{\alpha}{\dot{\varepsilon}} = 1.2 \times 10^{20}\,\mathrm{Pa-sec.}$$

The pluton (here 2 km in thickness) will then sink at a rate V (in m/sec) estimated by Stoke's Law

$$V = \frac{2gr^2\Delta\rho}{9\eta}$$

where r is the radius in meters of the "spherical" pluton. The pluton will sink 3km in 100 millions. But if the stress is doubled or the temperature is raised by about 100°C then the settling rate is increased by more than an order of magnitude.

The temperature of the lunar crust will evolve from a near constant 1300°K value to a linear profile ranging from 0°K at the surface to 1300°K a the base after about 100 million years ($\tau = \frac{X^2}{k}$ where k is the diffusivity, X the thickness of the crust). If we ignore the effects of cratering and the varying effects of insulation due to brecciation, it follows that mafic solidified plutons 10 km or less in thickness and of unspecified lateral extent become permanently trapped after 100 my within the upper crust, but not the lower crust. The existence of mascons at 3.9 By shows that the entire crust has now strengthened and can support stresses far in excess of those generated by mafic plutons.

From these observations, we make the following generalization:

1) The vertical crustal layering may be due to foundering of mafic plutons to the crust-mantle boundary but only in the first 100-200 million years of the solidification of the magma ocean.

2) If the lower mafic crust is due to foundering of mafic plutons and/or by underplating by mafic magmas, it follows that the KREEP layer originally trapped as a sandwich horizon between the anorthosite crust and the mafic cumulates must now exist within the crust, somewhere below the anorthosite layers and above or within the mafic zone (6).

3) The absence of mare basalt plutons is not due to a weak anorthosite crust especially after about 200 million since the end of the magma ocean. Even very dense high Ti mare gabbro plutons can be supported within the upper 30km of the crust. Either mare basalt volcanism did not precede the excavation of the multi-ringed basins or the mare volcanism was so energetic that most magmas were erupted directly to the lunar surface.

4) The development of an early mafic lower crust and the consequent stripping away of the anorthosite upper crust by impact processes, would create multi-ringed basins largely floored by dense mafic crust. This physical setting was ideal for the eruption of dense mare basalts to the lunar surface. The near absence of mare volcanism in the South Polar Aitkin Basin demonstrates that the conditions for the generation of mare volcanism lay deep within the Moon and that the physical conditions obtained within the lunar crustal were only of secondary importance; the mare source regions were not influenced by the cratering processes associated with multi-ring basin formation.

5) Having a stronger lower crust (the mafic crust is about 50x stronger than anorthosite) would have the effect of being able to support mascons during an earlier, overall hotter stage of lunar history.

References

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